Exploiting Nature's Telescopes

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The discovery of the microscope and telescope transformed science in the 17th century and brought into view new realms that were otherwise inaccessible. Now the extension offered by cluster lenses—nature's own telescopes—enhances our reach of the night sky and offers a glimpse of distant galaxies that would never ever be visible to us, no matter how far our technology progresses. Clusters of galaxies, the most massive and recently assembled structures in the universe, are the perfect astrophysical laboratories to tackle many pressing and key problems in cosmology today (for details, see review by Kneib & Natarajan 2011).

Einstein's theory of general relativity predicts the bending of light rays by intervening mass distributions. Dark-matter-dominated clusters of galaxies are the perfect lenses that deflect light from distant background populations of some of the earliest galaxies that likely assembled soon after the Big Bang. How these first galaxies formed and evolved is, of course, one of the key open questions in galaxy formation. The nature of dark matter remains elusive as well, despite our growing knowledge of how dark matter is distributed spatially in the universe, and that it aggregates in the most massive structures—clusters—clues to its nature are sparse at present.

Lensing reconstructions of the dark-matter distribution in clusters offers powerful checks on the validity of the currently accepted paradigm of a universe dominated by cold dark matter. Precision tests of this theoretical framework are possible with high-resolution mass reconstructions of galaxy clusters. High quality data can illuminate dark-matter properties, and cosmography with cluster lenses can provide strong constraints on cosmological parameters like dark energy. In addition to learning about clusters and their assembly history, gravitational lensing studies also offer the unique opportunity to study the population of highly magnified background sources with unprecedented detail. Therefore, cluster lensing offers an efficient way forward to pin down the sources that caused re-ionization of the early universe. However, to fully exploit the unique and potent capabilities of clusters, extremely high-resolution, deep images are needed, like those produced by *Hubble*'s Advanced Camera for Surveys (ACS).

A new opportunity to acquire just this kind of exquisite data has become possible with the **Frontier Fields Initiative**, undertaken with broad community input as a large *Hubble* survey beginning in Cycle 21. The observational strategy of the Frontier Fields program consists of ~140 orbits devoted per cluster/blank-field pair region, achieving AB ≈ 28.7–29 mag optical (ACS) and NIR (Wide Field Camera 3; WFC3) imaging with 560 orbits in Cycles 21/22. The six cluster candidates, all of intermediate redshift because it provides the optimal lensing geometry for distant sources, are Abell 2744 ($z = 0.308$); MACSJ0416 ($z = 0.396$); MACSJ0717 ($z = 0.545$); NACSJ1149 ($z = 0.543$); AbellS1063 ($z = 0.348$) and Abell 370 ($z = 0.375$). Propelled by the success of the earlier deep-field initiatives, namely *Hubble* Deep Field (pioneered by then-director Bob Williams in 1995) and the Ultra-Deep Field (in 2003), a *Hubble* Deep Fields Initiative Committee was set up by Institute director Matt Mountain in 2012 to recommend new initiatives with the *Hubble* that could attack fundamental problems in astrophysics. Weighing in advice from the astronomical community and deliberating on the set of critical science questions that could greatly advance our knowledge of early galaxy formation, the Committee recommended a program of six deep fields centered on strong lensing galaxy clusters in parallel with six deep flanking "blank fields." This recommendation was enthusiastically accepted, and the **Frontier Fields** program was developed with Jennifer Lotz and Matt Mountain as Co-PIs. *Spitzer* has also committed to supporting this effort and is providing commensurate data. A total of 50 hours of integration with *Spitzer*'s IRAC instrument are being spent in each of the 3.6 and 4.5 micron channels (**http://ssc.spitzer.caltech.edu/warmmission/scheduling/approvedprograms/ddt/frontier/**).

The science goals of these new deep fields are: (1) to understand the detailed distribution of dark matter in clusters and compare with theoretical models; (2) to use the magnifying power of cluster lenses to unravel currently inaccessible galaxy populations at $z = 5$–10 that are intrinsically 10–50 times fainter than any presently known, consolidating our current understanding of the stellar mass assembly of sub-L_* galaxies at the highest redshifts; (3) to provide the first statistically meaningful morphological characterization of star-forming galaxies at $z > 5$, and to find $z > 8$ galaxies stretched out enough by cluster lensing to discern internal structure and/or magnified sufficiently for spectroscopic follow-up.

The ongoing *Spitzer* Frontier Fields program focuses on complementary science goals to (a) better understand the stellar masses and star-formation histories of sub-L_* galaxies at the highest redshifts, (b) provide the first statistically meaningful characterization of the stellar populations in star-forming galaxies at $z > 5$, and (c) find high redshift $z > 8$ galaxies magnified sufficiently by cluster lensing to enable spectroscopic follow-up.

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Details of the observational program can be found at **http://www.stsci.edu/hst/campaigns/frontier-fields/HST-Survey**. A timely workshop titled "**Cluster Lensing: Peering into the past, planning for the future**" was convened in 2013, followed by a recent workshop highlighting first science results "**Yale Frontier Fields Workshop: Shedding Light on the Dark Ages and Dark Matter**" held in New Haven in November 2014.

Since magnification maps of these lenses are crucial to extracting science from the public data, Jennifer Lotz, Ken Sembach, and Neill Reid at the Institute selected five groups to provide preliminary magnification maps prior to the start of new observations. These maps provided by independent groups are available publicly for the astronomical community at the Mikulski Archive for Space Telescopes (MAST) archive **http://www.stsci.edu/hst/campaigns/frontier-fields/**.

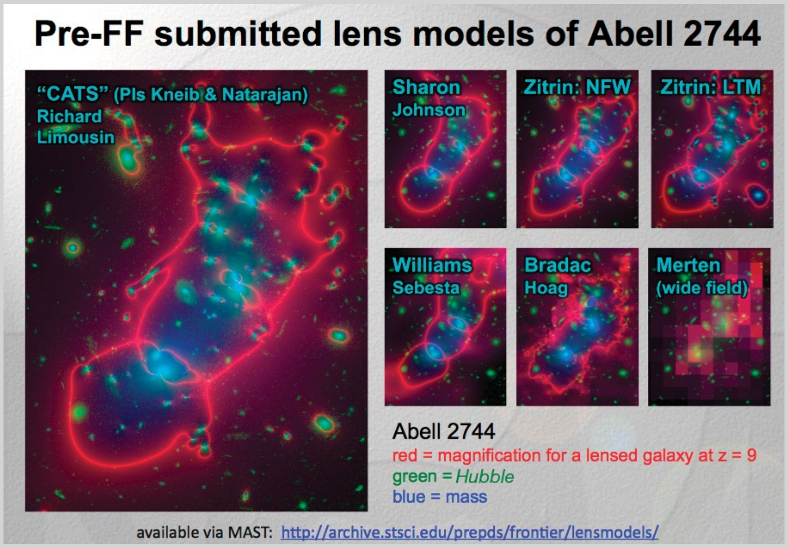

Figure 1: Preliminary magnification maps for one the FF clusters, Abell 2744, provided by selected map-making groups prior to the new data. These maps were constructed with existing *Hubble* data (prior to the *Hubble* FF program). Similar magnification maps computed for background sources at $z = 9$ for all 6 frontier field targets are available at **http://archive.stsci.edu/prepds/frontier/lensmodels/**. The scale of the map is the field of view of the WFC3-IR detector [approx. 2 arcmin × 2 arcmin].

In addition, an exercise to calibrate the reconstruction methodology is underway. It compares the models and maps produced for a simulated cluster by different groups deploying independent mass modeling techniques. The author, Dan Coe, and Massimo Meneghetti have recently finished Phase II of this exercise and upon completion of the next (final) stage, the results of comparing maps submitted by various groups for a set of simulated clusters will be published in the refereed literature and also be made available online.

The first science results from Abell 2744 and MACS0717.5+3745, the two FF clusters with completed observations, are extremely exciting. Below are a few glimpses of some of these new findings from characterizing the mass distribution of the lenses and exploiting them as telescopes to detect high-redshift galaxies and supernovae. More details can be found on the Yale Workshop site where PDF files of all talks are available at the following URL: **http://www.astro.yale.edu/yale_frontier_workshop/schedule.php**.

Characterizing the cluster lens

Several groups have published dark-matter maps for the first two FF clusters, Abell 2744 and MACS0416. The magnification maps from one group (Grillo et al. 2014) are shown in Figure 2, and the combined strong + weak lensing reconstruction for Abell 2744 (Jauzac et al. 2014b) is shown in Figure 4. As expected, these two massive lensing clusters have complex geometries with merging sub-clusters, thus requiring multiple large-scale components and numerous smaller galaxy-scale sub-halos to model their mass distributions. In contrast to previous *Hubble* data, the quantum leap in the number of multiple images that are now available to constrain the models is unprecedented. In the case of Abell 2744, with the FF data we now have ~250 multiple images that are used in the reconstructions, thereby bringing down the statistical errors to the few percent level compared to earlier work. With *Hubble* FF data, it turns out that modeling techniques require refinement and honing, where previously with sparser data the opposite was true—the data was insufficient to yield unique models. We will be able to provide robust quantitative estimates for systematic errors as soon as the model comparison exercise has concluded.

Figure 2: The public *Hubble* FF data for the cluster Abell 2744: ACS Optical (*left panel*) and the WFC3/IR (*right panel*).

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As an important and unexpected bonus, the FF clusters to date have yielded a total of 25 SNe out to $z \sim 1.5$ with two confirmed background supernovae, one that is singly imaged and magnified, and the other an extremely rare quadruply imaged Einstein cross at $z = 1.491$ lensed by an early-type galaxy

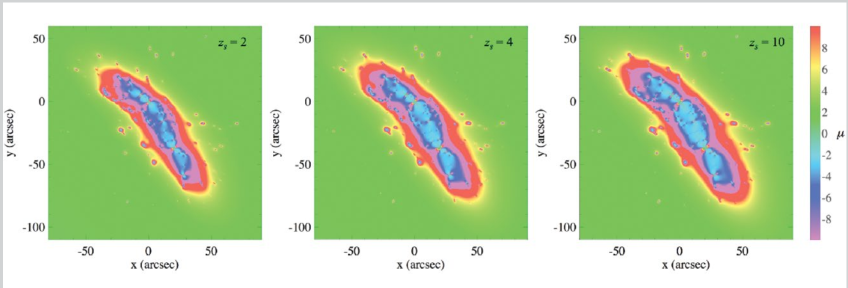

Figure 3: The magnification maps of the FF cluster MACS0416 for sources at $z = 2$, 4 and 10 from the Grillo et al. (2014) best-fit model that comprises of 2 large-scale PIEMD models for the smooth component of the dark-matter distribution and 175 smaller galaxy-scale halos.

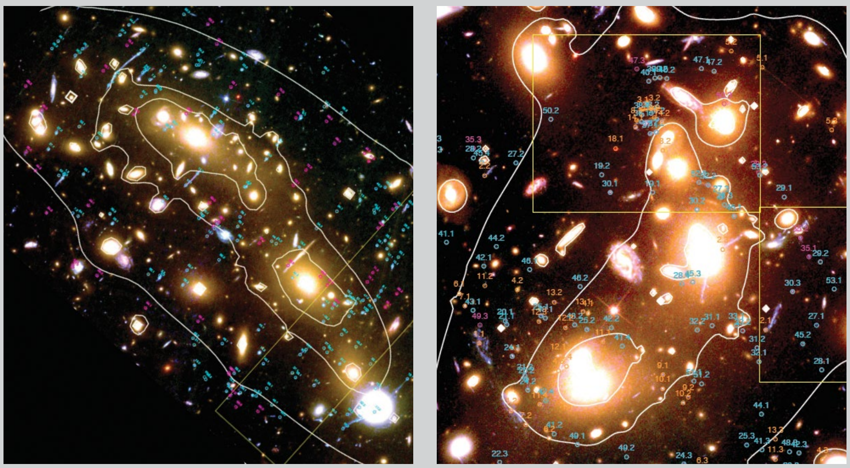

Figure 4: The reconstructed mass distribution in Abell 2744 (*right panel*) and MACS0416 (*left panel*) obtained with strong lensing data from the *Hubble* FF program (published by Jauzac et al. 2014a,b). These particular mass models of Abell 2744 utilize 159 images from 51 sets of multiples and 194 multiply imaged sources in MACS0416. These mass maps have unprecedented small statistical errors compared to models generated from earlier shallower *Hubble* data.

cluster member boosted by the overall cluster in MACS1149 (shown in Figure 5). This unique system is likely to provide strong constraints on the mass of the cluster galaxy as well as the cluster (Kelly et al. 2014). It will also provide an important test for the lens modelers. The predicted lens model magnifications for one of the singly imaged, spectroscopically confirmed Type Ia supernova detected by Rodney et al. (2014)—HFF14Tom at $z = 1.33$ in Abell 2744—are systematically and significantly higher than estimated from the fact that it is a standard candle. At a distance at 40 arcseconds from the cluster center at the edge of the strong lensing region, this suggests (as suspected) that all lens models contain systematic biases that at present are not well quantified, and uncertainties remain under-estimated.

Another candidate, the supernova HFFJan14, has now been confirmed to be a Type Ia (Foley et al. 2014). A spectrum obtained from Gemini-North in the wavelength range 460–965 nm confirms this spectral classification. This SN, with a measured redshift of $z = 0.305$, however, lies in the foreground of the cluster Abell 370 consistent with photometric redshift estimates. This one, therefore, does not provide any constraints on the mass modeling. Another strongly lensed transient object consisting of two images—originally believed to be an SNe—appears to not be so. This peculiar object, HFF14Spo, appears in the optical, rises in luminosity by ~1 magnitude, and then fades in less than 3 rest-frame days. The nature of this object is, as yet, undetermined. On a diagnostic plot of the peak luminosity versus characteristic time-scale in days, it appears to be similar to the "intermediate" luminosity SN-like objects detected in a recent PTF survey by Kasliwal et al. (2011). It is unclear if this kind of new optical transient, including HFF14Spo, are standard candles.

One of the primary science drivers for the *Hubble* FFs was the ability of these massive cluster lenses to bring into view faint, high-redshift, $z > 6$ populations of galaxies to determine the properties of the earliest structures to form and their role in re-ionization of the universe. Using the preliminary magnification maps (with pre-HFF data) made available to the astronomical community, as well as the maps made with *Hubble* FF data, several groups have made independent determinations of the slopes and normalizations of the luminosity function (LF) of sources at $z = 6, 7, 8$, and 9. Current determinations from the *Hubble* FF data are broadly in agreement with prior estimates from the deep blank fields. There is, however, considerable dispersion amongst groups in the determined value of the faint end slope of the LF at $z = 8$ and 9 (Atek et al. 2014; Oesch et al. 2014; McLeod et al. 2014; Laporte et al. 2014; Vanzella et al. 2014). Crucial to this determination is the estimation of completeness where the uncertainties in the magnification maps come into play. The variation in the reported values for the faint-end slope of the LF likely arises from differences in how the completeness is assessed and the reliable identification of high-z galaxies given the uncertainties in their photometric redshifts.

With updated magnification maps from the full FF data, the various LFs should come into better agreement. Analyzing drop-out galaxies from the full FF data of Abell 2744 and the flanking fields Ishigaki et al. (2014) report tension between the determined UV star-formation rate density from faint end LF slope and the measured large Thomson scattering depth inferred from CMB experiments. In addition, grism spectra of the *Hubble* FF sources from the GLASS project have started to reveal emission lines in $z > 6$ lensed galaxies (Schmidt et al. 2014). Another exciting find has been the reported discovery of a candidate lensed $z \sim 10$ galaxy using the photometric drop-out technique, potentially yielding one of the least luminous galaxies to be detected at this redshift if its spectroscopic redshift is confirmed (for details see Zheng et al. 2014 and Zitrin et al. 2014). Vigorous multi-wavelength follow-up is also underway.

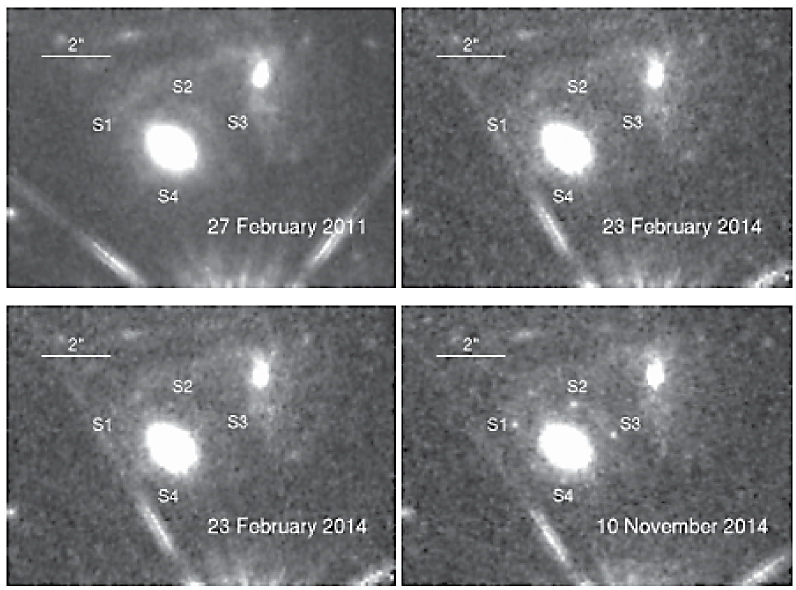

Figure 5: The newly discovered, rare quadruply imaged Einstein cross—a supernova in a background spiral galaxy arm lensed by a cluster elliptical in MACS1149. In honor of one of the pioneers of lensing, Sjur Refsdal, this SN bears the name Refsdal. Images of the lensing system are from archival WFC3-IR observations in the F140W filter. All exposures obtained prior to 3 November 2014 show no evidence for variability at any of the positions associated with SN Refsdal.

Cluster modeling comparison exercise

In order to quantify the systematic errors incurred in cluster mass modeling, we have been conducting a comparison of independent methods employed by various groups. Lensed images from a simulated cluster were provided to the participant groups and sets of well-defined metrics were devised for comparing models to the true values. Starting with a simple cluster in Phase I of the exercise, we have just completed Phase II that required the reconstruction of a more complex cluster mass distribution. We have now provided the participating groups' analysis of the performance of their codes *viz*-à-*viz* the true maps for the first two simulated clusters in order to help them refine their methods. We intend to conclude this effort by providing the modelers with one more simulated cluster prior to publishing the results of this exercise in 2015. The results of this entire exercise will be made available to the community.

Even the first, early results from the *Hubble* Frontier Fields are revolutionizing our understanding of clusters and the distant objects that they serendipitously bring into view. By the time the FF program concludes we might well be forced to re-conceptualize clusters and perhaps all dark-matter concentrations in the universe!

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